Transmission Lines*

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Describing methods whereby high quality sound reproduction in auditory perspective can be accomplished over long distances, this discussion centers largely upon a description of the exact technique employed in providing communication transmission circuits for the Philadelphia-Washington demonstration. Problems that might be involved in carrying out such transmission on a more widespread scale also are touched upon.

MICROPHONES have been described that will pick up without noticeable distortion all the sounds given forth by a symphony orchestra. Loud speakers and amplifiers also have been described that will accurately reproduce this highest quality music in its full range of tone quality and volume. Therefore, the situation obviously requires connecting transmission paths so perfect in their characteristics that reproduction 100 or 200 miles away may not suffer in comparison with reproduction which may be only 100 or 200 feet from the source of music.

There are several respects in which a long line circuit possibly may distort the speech or music passed over it, unless considerable effort is expended to overcome these tendencies. For example, there may be frequency-amplitude distortion; i.e., all the notes and overtones may not be transmitted with the proper relative volumes. Similarly there may be phase or delay distortion, the different frequencies may not arrive at the receiving end of the line circuit in the same time relationships in which they originated. A line circuit is subject also to possible inductive disturbances from other communication circuits ("crosstalk"), or from power or miscellaneous circuits which cause "noise" at the receiving terminal. If the circuit contains amplifiers, transformers, and inductances having magnetic cores, it is subject to possible nonlinearity effects; i.e., the current at the receiving end of the line may not follow exactly the amplitude variations of the current applied to the transmitting end or, what is more important, spurious intermodulation frequencies may be generated within the transmission circuit and mar the purity of the musical tones. The problem of reproduction in auditory perspective, using two or three paralleling

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channels, also adds the requirement that these channels must be substantially identical in their transmission characteristics.

With the exception of the last, all these aspects of the problem are, of course, not peculiar to symphony music transmission. They exist as part of the problem of satisfactorily transmitting any telephone message. However, the requirements of this new high quality transmission have set a new high standard of refinement, even as compared with that required for ordinary radio chain broadcasting. For example, ordinary telephone message transmission commonly is carried out by circuits having a frequency range not exceeding 200 to 3000 cycles per second. Much present-day radio broadcasting involves a transmission band only from about 100 to 5000 c.p.s. This new high quality transmission, however, requires a range from approximately 40 to 15,000 c.p.s. Further, with reference to the required freedom from interference, ordinary radio broadcasting seldom exceeds a volume range greater than 30 decibels. The new high-quality system, however, requires a volume range of at least 65 db, which is more than 3,000,000 to 1 expressed as a power ratio.

In considering the specific problem of transmitting from Philadelphia to Washington for the demonstration given on April 27, 1933, several alternative methods of providing the required transmission paths presented themselves. The arrangement chosen consisted in bridging the distance between the two cities by means of carrier channels over cable conductors. From the telephone toll office in Philadelphia to the toll office in Washington, three carrier transmission paths were provided in which the music frequencies were stepped up from their normal position in the audible range to considerably higher frequencies. The frequency range from 40 to 15,000 c.p.s. picked up by the microphones was transmitted over line circuits in a range from 25,000 to 40,000 c.p.s. After being thus stepped up in frequency, the high frequency currents were applied to three non-loaded pairs in an all-underground cable which was equipped with repeaters at approximately 25-mile intervals. At Washington, step-down or demodulation apparatus restored the frequencies to their normal position in the spectrum.

For transmission between the auditorium in Philadelphia and the toll office there, a distance of approximately three miles, and for transmission in Washington between the telephone toll office and the auditorium, about half this distance, normal frequency transmission over small-gauge pairs in ordinary exchange cables was employed.

The use of the carrier method for the long distance transmission has several advantages. In general, it permits multiplex operation; i.e., more than one message or program on the same pair of wires. As a

matter of expediency in this particular case this feature of operation was not used, and three separate pairs were employed, one for each channel. In the future the same technique undoubtedly would permit two or possibly more of these extra-broad-band transmission paths to be obtained on the same pair of conductors. The most important reason for choosing the carrier method rather than transmission in the natural audio-frequency range in this particular case was that, because all other transmission circuits in the same cable were at a considerably lower frequency and because the lead sheath of the cable acts efficiently at the high frequencies to shield the pairs from induced disturbances from the outside, it offered a special freedom from crosstalk and noise.

With these arrangements, which will be described in somewhat greater detail in what follows, requirements of transmission were met very satisfactorily and the reproduction of the symphony music in Washington with the orchestra playing in Philadelphia suffered not the least in comparison with the reproduction of the same program in an auditorium in Philadelphia located but a few feet from the hall in which the orchestra played. It is believed that, if necessary, by the use of the same principles, line circuits may be set up and comparable quality reproduction given throughout the country. However, as will be evident from part of the discussion which follows, in some respects the problem of meeting the requirements in transmission between Philadelphia and Washington was not as difficult as might be encountered in other localities. Hence even more complex arrangements might be necessary if it were desired to establish such transmission circuits to other points, and particularly for greater distances.

Line Circuits

There are several all-underground cables between Philadelphia and Washington. As described in a paper[1] by Clark and Green given before the A. I. E. E. in 1930, recently laid cables contain several 16-gauge conductors distributed throughout the cross section of the cable for possible use as program circuits in chain broadcasting. These pairs, however, ordinarily are loaded and equipped with repeaters at approximately 50-mile intervals so that they transmit a frequency range up to about 8000 c.p.s.

In one of the cables several pairs of this type had not yet been loaded, and these pairs were used for this newer transmission. Because of the higher frequencies employed and the greater attenuation encountered, it was necessary to install repeaters at more frequent intervals. As may be noted in Fig. 1, the normal cable layout between Philadelphia and Washington includes two intermediate repeater

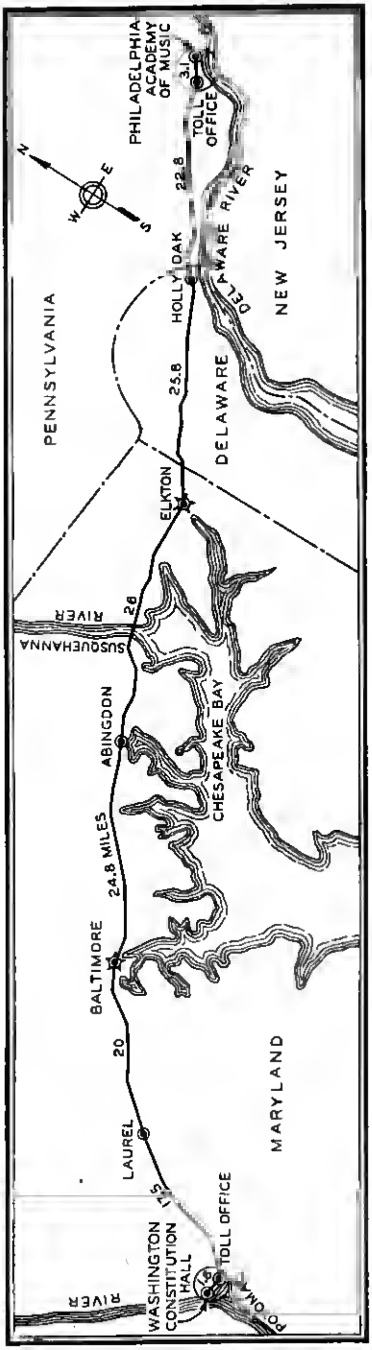

Fig. 1—Geographical layout of 3-circuit communication line used to carry Philadelphia symphony music to Washington, D. C., for reproduction in auditory perspective.

stations, one at Elkton and one at Baltimore. Additional repeater stations were established accordingly at in-between points—Holly Oak, Abingdon, and Laurel. One of these repeater points, Holly Oak, was established in a local telephone office. No such convenient housing existed at the other two points, and it was necessary to establish new repeater stations. These were small metal structures large enough to house only the repeaters, their power supply, and testing equipment. This apparatus was arranged to be normally non-attended, various switching actions being remotely controlled from the nearest regular repeater station.

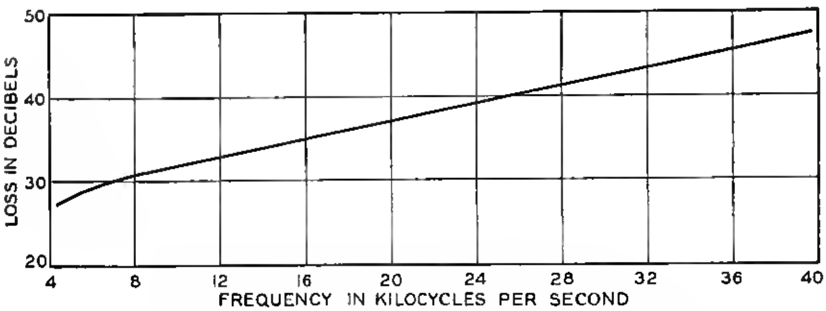

Fig. 2—Line attenuation characteristic of typical repeater section.

The line attenuation between repeater points is shown in Fig. 2. It may be noted that the attenuation is approximately 50 db for the highest carrier frequency involved. A diagram showing the variations in power level as the carrier waves traverse the complete circuit is shown in Fig. 3. Because of the variation in attenuation over the

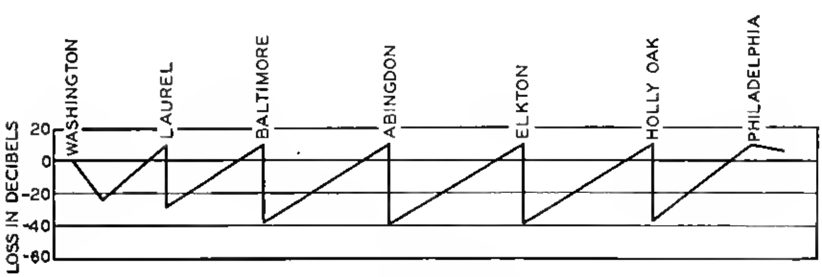

Fig. 3—Transmission level diagram.

frequency range employed it was necessary, of course, to use equalizers at the input of each repeater; i.e., networks having an attenuation variation with frequency approximately the inverse of that of the line circuit.

Noise

In setting up these circuits various tests, including measurements of noise currents picked up by the conductors to be employed, were made prior to the actual installation of the apparatus. It was discovered that on the cable circuits north of Baltimore these pairs were picking up sufficient noise even at the higher frequencies to constitute a possible limitation in the volume range that might be delivered. This noise was generated chiefly as a by-product of relay and other similar operations within the Baltimore office and was propagated over the longitudinal circuits of various pairs in the cable from which, by induction, it entered the special selected pairs. As a remedial measure, longitudinally acting choke coils applied to all but the specially selected pairs in the cable greatly reduced the noise. Shielding and physical separation were employed in the Baltimore office to prevent induction between the repeaters and the connection to the main cable. If it is desired to use existing cables for carrier transmission, particularly for such high grade transmission circuits, it seems likely that filtering arrangements of this kind, or other precautions, generally will be required.

Carrier Apparatus

The carrier system employed may be characterized briefly as single-sideband carrier-suppressed, with perfectly synchronized carrier frequencies of 40,000 c.p.s. Most present-day commercial telephone carrier systems are of the single-sideband carrier-suppressed type. Suppressing one sideband saves frequency space and suppressing the carrier reduces the load on the line amplifiers or repeaters. Ordinarily the exact synchronization of the carrier frequencies at the sending and receiving ends is not required for message telephone service.

Obtaining a single sideband after modulation commonly is carried out by providing band filters which transmit the desired sideband and suppress the unwanted sideband. For the requirements of message telephone transmission this does not impose severe requirements in the design of filters because audio frequencies less than about 100–200 c.p.s. ordinarily are not transmitted, in which case, if the filter in suppressing the unwanted sideband tends to cut off the lower frequencies of the desired sideband, it is not important.

For the requirements of this new high quality system, however, where it was desired to transmit all frequencies to at least as low as 40 c.p.s., the problem was considerably more difficult. Two alternatives presented themselves in the design of the required filters. The first consisted in attempting to provide the required selectivity in the filters themselves, perhaps supplementing the actions of induc-

tance coils and condensers (which normally make up such a filter structure) by quartz crystals to provide the sharp selectivity required on the sides of the band. The other alternative consisted in providing a filter of moderate selectivity so that in the neighborhood of the carrier frequency the unwanted sideband is not completely suppressed, and in arranging that the resultant reproduced music at the receiving terminal is obtained by the proper coordination of the desired and the vestige of the unwanted sideband. The "vestigial" sideband method was decided upon. Although this does not require filters having particularly sharp selectivity on the sides of the band, it does, however, impose more severe requirements upon the control of the phase characteristics of the filters in the neighborhood of the carrier frequency. It makes it necessary also to have the carrier frequencies at the sending and receiving ends not only synchronized, but phase controlled as described later.

For the modulating elements in the system at both the sending and receiving terminals, copper oxide rectifying disks were chosen. These elements can be made very simple. In stability, with respect to transmission loss and the ability to suppress the unwanted carrier frequency by balanced circuits, this arrangement is superior to the usual vacuum tube circuits.

In Fig. 4 is shown schematically the arrangements of the carrier circuit at the transmitting and receiving ends. At the transmitting terminal the circuit from the microphones is led first through low- and high-pass filters to limit the bands to the desired width; i.e., 40 c.p.s. to 15,000 c.p.s. The 40-cycle limiting filter was included because tests had demonstrated that lower frequencies are not required for the satisfactory transmission of music of symphony character, and because it was feared that occasional high energy pulses of subaudible frequency might cause overloading. When these 40-cycle filters are omitted, as was done in tests, the carrier channels are capable of transmitting frequencies down to and including zero frequency, a characteristic which could not possibly be obtained in a single sideband system by other than such a vestigial sideband technique.

As may be noted further in Fig. 4, carrier current is supplied to the rectifying disks of the modulator along with the incoming music frequencies. The balancing connection of the four rectifying disks making up the modulator is arranged to suppress the carrier frequency, the final degree of suppression being adjusted by means of the variable condenser and resistance shown, which were included to make up for slight dissimilarities in the characteristics of the individual copper disks. A very high degree of carrier suppression can be achieved by

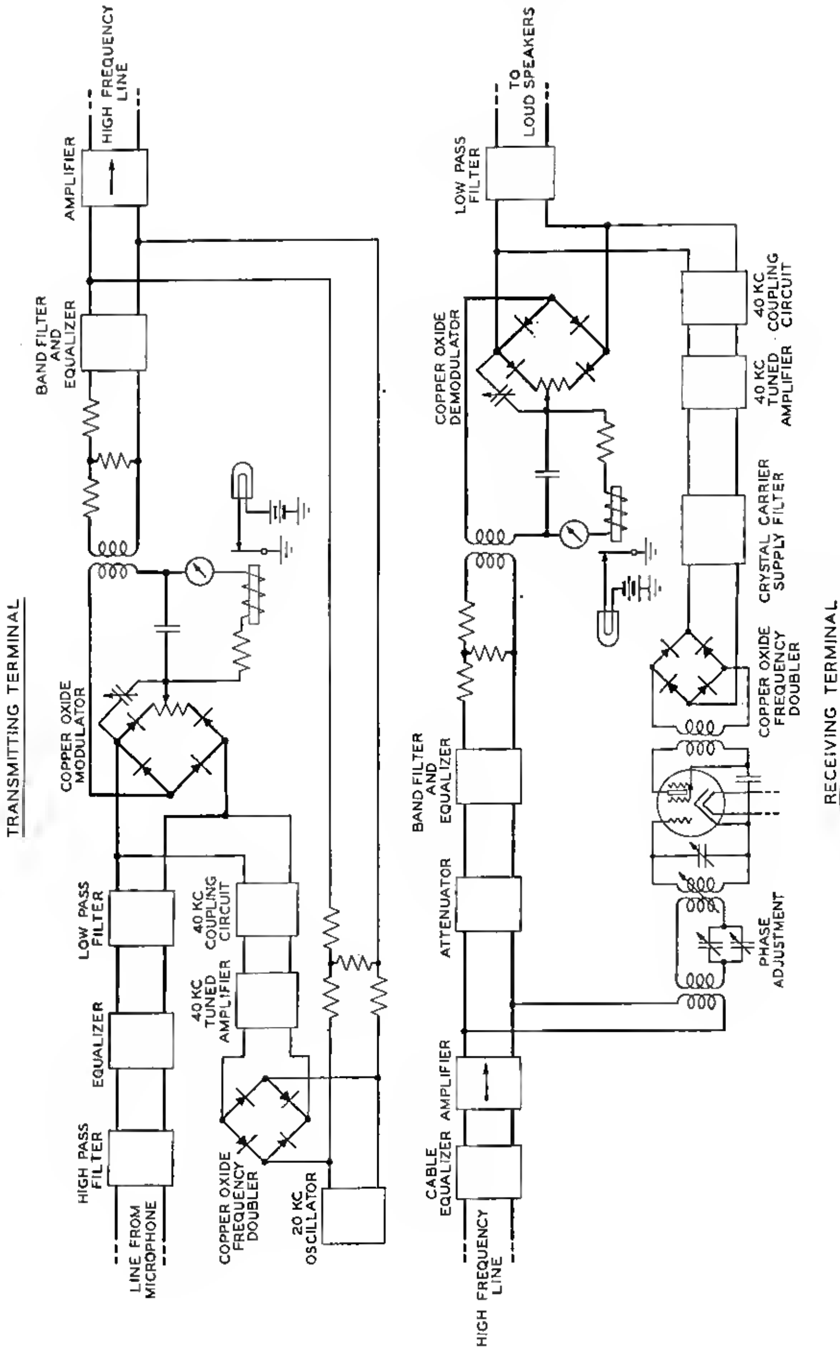

Fig. 4—Schematic diagram of carrier terminal circuits.

this means. No difficulty was experienced in maintaining a ratio of at least 60 db between the carrier voltage applied to the unit and the residual carrier current not completely balanced out. Over short periods an even higher degree of balance can be readily obtained.

There is a certain amount of electrical noise generated in the rectifying disks over and above that caused by thermal agitation [2, 3] effects. The amount of this noise compared with the maximum permissible modulation output determines the volume range possibilities of a modulator of this type. Measurements indicated that this range was approximately 90 db, which obviously was more than sufficient to meet the requirements desired.

The circuit includes a relay and a meter through both of which flows the d.-c. component produced by the rectification of the carrier frequency. These supplementary units give a check on the magnitude of the carrier supply and afford an alarm in case of failure. From the modulator unit the circuit is connected to the band filter which transmits only the lower sideband lying between approximately 25,000 and 40,000 c.p.s. and the vestige of the upper sideband. From the band filter the currents are led to an amplifier and thence to the line circuit leading to the farther terminal.

It may be noted that at the transmitting terminal the 40,000-cycle carrier current is derived from a 20,000-cycle oscillator by passing its output through a series of copper oxide rectifiers connected to form a frequency doubler. Part of the originally generated 20,000 cycles also is connected to the input of the transmitting amplifier and sent over the line to be used in producing the 40,000-cycle carrier supply for demodulation.

At the receiving terminal a similar modulation or demodulation process occurs through the use of copper oxide disk circuits. A relay and meter also are included in the circuit to check the carrier supply, in this case providing also a check or pilot of the transmission over the long line circuit. The 20,000-cycle synchronizing current is selected at the receiving terminal, amplified and applied to a frequency doubler, and thence applied to the demodulator circuit. The input of this carrier supply circuit includes also a phase adjusting variable condenser arrangement so that the phase of the carrier supplied to the demodulator may be adjusted properly in relation to that of the carrier supplied to the modulator at the sending end. An interesting feature of the receiving terminal carrier supply is the quartz crystal filter employed to select the 40,000-cycle carrier after frequency doubling. The transmission characteristic of this extremely selective filter is shown in Fig. 5.

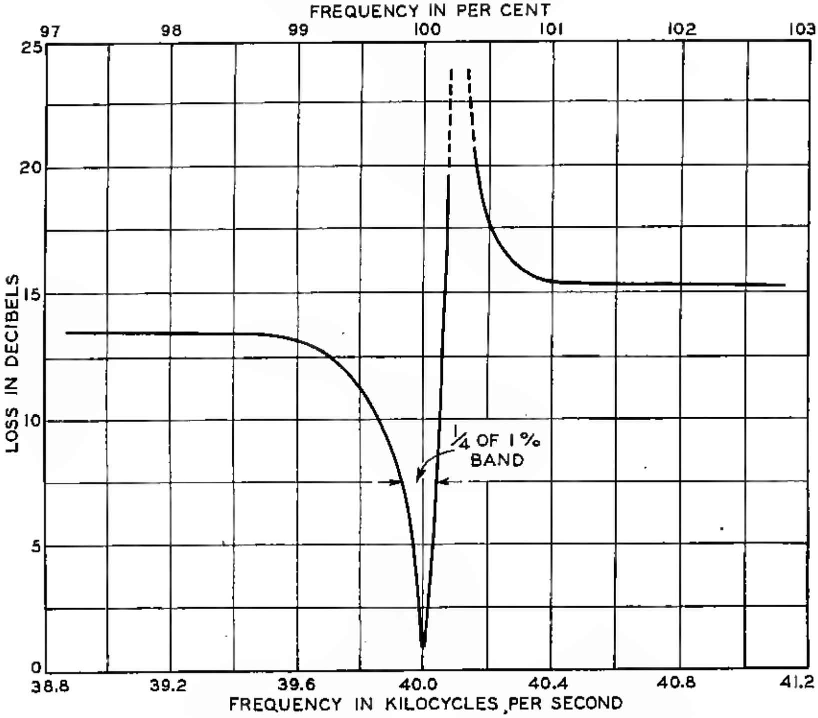

Fig. 5—Transmission characteristic of carrier supply crystal filter.

Filters

The transmission characteristics of the carrier channels are determined largely by the filters and associated equalizers. The filters principally affecting transmission are the band filters. Identical units are employed at the sending and receiving ends. The transmission and phase shift characteristics of one of these units are shown in Fig. 6. These band filters are equalized to produce the desired squared band characteristic.

The characteristics in the frequency region near the carrier (i.e., at 40,000 cycles) are shown on a large scale. This region is of particular interest because it is here that the degree of success in the application of the vestigial sideband method, for the purpose of insuring the satisfactory transmission of the low music frequencies, is determined. If for a given frequency interval above the carrier the phase change is arranged to be equal and opposite to that of the same frequency interval below the carrier, then in the action of demodulation the demodulated current produced by the action of one sideband adds

itself arithmetically to that produced by the other sideband. It will be noted that this desirable phase characteristic has been achieved closely in the characteristics shown. If, in addition, the attenuation

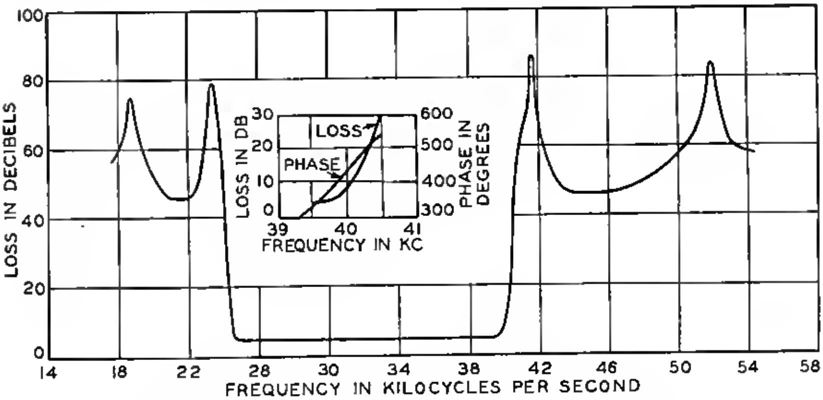

Fig. 6—Transmission and phase characteristics of band filter.

loss in the filter is adjusted so that the sum of the regular and vestigial sideband amplitudes corresponding to the low music frequencies is substantially constant and equal to the amplitude of the frequencies at midband, the desired flat transmission characteristic is assured.

As was noted previously, this action can be carried out only if the phase angle of the receiving carrier is properly related to that of the sideband frequencies and, in turn, to the carrier applied to the modulator at the transmitting terminal. The curves shown in Fig. 7

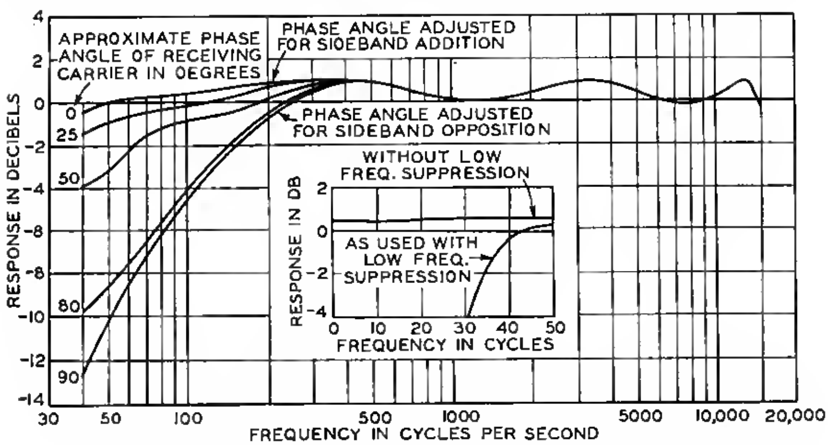

Fig. 7—Over-all transmission characteristics as a function of the phase relation of the receiving carrier.

illustrate the influence that the phase adjustment of the carrier frequency has on the transmission of the lower frequencies in a system of this kind.

The upper curve shows the transmission frequency characteristic of one of the carrier channels measured from terminal to terminal between distortionless lines, when the phase angle of the receiving carrier is adjusted for its optimum value. Under these conditions the vestigial sideband and normal sideband supplement each other in their effects to produce substantially flat transmission. (The insert indicates the sustained transmission toward zero frequency when the 40-cycle highpass filter is omitted from the circuit.) It may be noted also that with this proper phase adjustment the full band transmission characteristic provided is substantially flat within a fraction of a decibel from 40 c.p.s. to 15,000 c.p.s. The lower curves indicate successively what happens if the phase angle of the receiving carrier is adjusted different amounts from the optimum adjustment. It may be noted that for a 90-degree departure the transmission of a 40-cycle tone over the carrier channel would suffer more than 12 db in comparison with a 1000-cycle tone.

Repeaters

As noted previously, the line circuit between Philadelphia and Washington included five intermediate repeater points. A schematic drawing of the apparatus installed at each point is shown in Fig. 8.

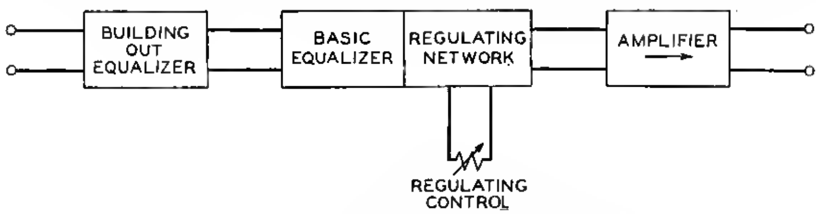

Fig. 8—Schematic diagram of repeater station apparatus.

The amplifiers at these points, as well as those used at the transmitting and receiving terminal, consisted of a new form of amplifier employing the principle of negative feed-back. The principal virtues of amplifiers of this type are their remarkable stability with battery and tube variations and great freedom from nonlinearity or modulation effects. Each amplifier is supplemented at its input by an equalizer designed to have its attenuation approximately complementary in loss to that of the line circuit in a single section. The amplifiers actually employed for the purpose were taken from a trial of a cable

carrier system described in a recent A. I. E. E. paper by A. B. Clark and B. W. Kendall.[4]

The losses in the cable circuits do not, of course, remain absolutely constant with time, and slow variations due to change of temperature are compensated for by occasional adjustments of the variable equalizer arrangements provided. These adjustments were required only infrequently; approximately at weekly intervals because in an underground cable the temperature experiences only slow, seasonal variations.

As noted, new repeater stations were established at two points. The housing arrangements for one of these points, Abingdon, is shown in Fig. 9. The equipment at this repeater point also included relays remotely controlled from the nearest attended repeater station to permit the repeaters to be turned on and off at will and the power supply, which consisted of storage batteries, to be switched from the regular to the reserve battery or either battery put on charge if required.

Fig. 9—Interior and exterior of special intermediate repeater station at Abingdon, Md.

Over-All Performance

While the system was set up specifically to provide transmission for the demonstration into Washington on April 27, 1933, it was operated over a period of several weeks and complete tests and measurements were carried out for the purpose of gathering information on cable carrier systems. The complete layout of apparatus and lines provided between Philadelphia and Washington is shown in Fig. 10.

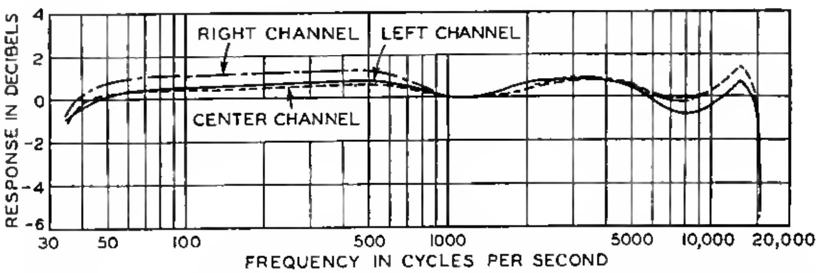

Fig. 11 (right)—Frequency characteristics over carrier channels used between Philadelphia and Washington, D. C.

The over-all frequency transmission characteristics of the three channels that were set up are shown in Fig. 11. These curves differ from those shown in Fig. 7, and include the complete high frequency line circuit with its 150 miles of cable, repeaters, equalizers, and other equipment. It may be seen that between the desired frequency limits the circuit is substantially flat in transmission performance to within $\pm$ 1 db. Various noise measurements made on the over-all circuit indicated that the circuits fully met the requirements that had been set up, and that the line and apparatus noise was inaudible in the auditorium at Washington even during the weakest music passages. The circuit also was found to be free from nonlinear distortion to a satisfactory degree. Harmonic components generated when single-frequency tones were applied to the channels at high volumes were found with one unimportant exception to be more than 40 db below the fundamental.

As a means of obtaining a further increase in volume range, which was not actually required for this demonstration, tests were made with a so-called predistortion-restoring technique. In this the higher frequency components of the music were transmitted over the carrier channels at a volume much higher than normal in relation to the volume of the lower frequencies. By this means any noise entering the carrier channels at frequencies equivalent to the higher music frequencies is greatly minimized in effect.

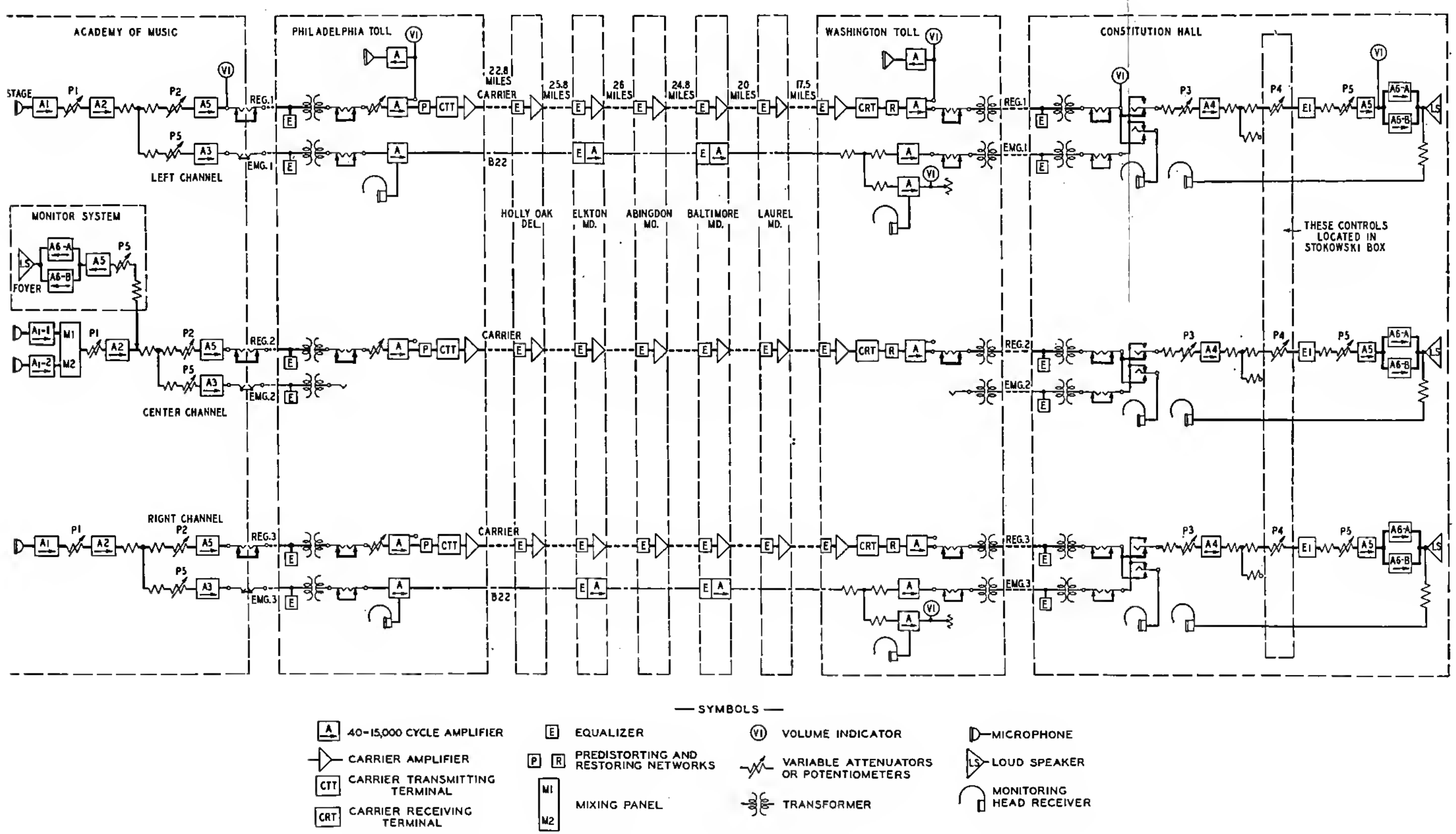

Fig. 10—Schematic diagram of circuit layout for 15-kc channel used for symphonic program demonstration.

This predistortion is accomplished by including in the circuit at the input to the modulator a network having relatively high loss for the lower frequencies and tapering to low loss for the higher frequencies. Its maximum loss is compensated for by adding in the circuit an equivalent amount of additional amplification. The characteristics of such a network are illustrated in Fig. 12. To restore the normal volume relationships between the different tones and overtones a

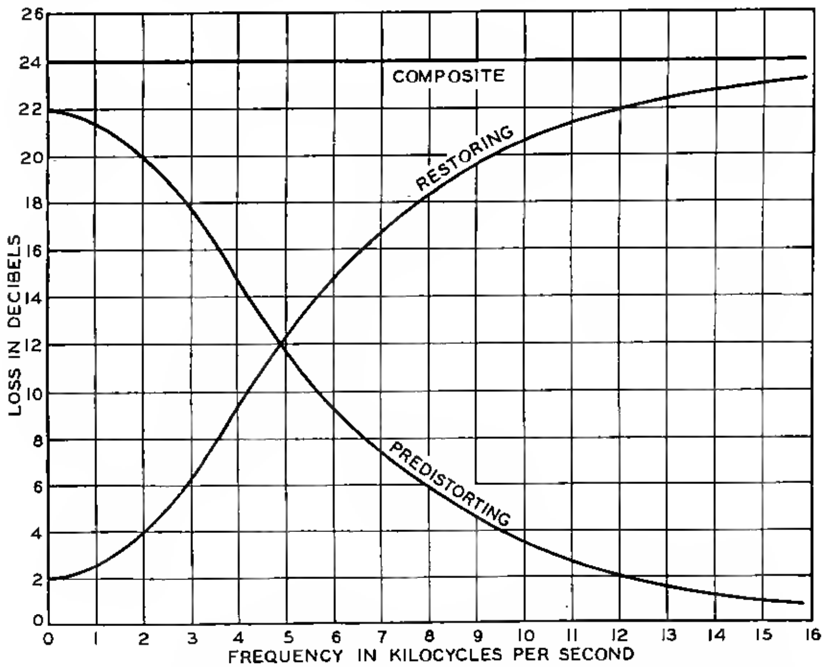

Fig. 12—Attenuation characteristics of "predistorting and restoring" networks.

restoring network having complementary transmission frequency characteristics is, of course, included at the output of the receiving circuit. It was found with this predistortion-restoring technique that a volume range increase of something like 10 db could be obtained over the circuits described.

There is available also another method which might have been employed for obtaining a further increase in volume range. This method, the so-called volume compression-expansion system, very likely will be necessary if in the future it is desired to obtain such high quality circuits on long routes where the carrier frequency range is being used also for regular telephone message transmission or for other purposes, and where the problem of freedom from noise and crosstalk

no doubt will be more serious than experienced in the Philadelphia-Washington demonstration. Such a volume compression-expansion system requires additional apparatus at the sending and receiving terminals of the line circuit. At the sending end this apparatus is used to raise in volume the weak passages of the music or other program for transmission over the line circuits in order that the proper ratio between the desired program and unwanted noises may be retained. At the receiving terminal coordinating apparatus reexpands the compressed volume range to the volume range originally applied to the transmitting terminal.

In the demonstration, to provide supplementary control features required by Dr. Stokowski at Washington for communicating with the orchestra at Philadelphia, additional wire circuits were established between these points. Order wire circuits also were provided for communication between the terminals and repeater points to make possible the location troubles if any should arise. Rather elaborate switching means were included at the terminals to permit switching the carrier channels to different microphones and to different amplifier equipment at the loud speaker end. To take care of the contingency of a cable pair failure, spare pairs of wires were made available to be switched in at short notice. Fortunately, none of the reserve facilities actually were required for the demonstration.

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